$|q/p|$ Measurement from $B^0 \to D^* l\nu$ Partial Reconstruction

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Abstract

We present a new measurement of CP violation induced by B^0 $\overline{B}^0$ oscillations, based on the full data set collected by the *BABAR* experiment at the PEPII collider. We use a sample of about 6 million $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu_\ell}$ decays selected with partial reconstruction of the D^{*+} meson. The charged lepton identifies the flavor of the first B meson at its decay time, the flavor of the other B is determined by kaon tagging. We determine the parameter $\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$.

1 Introduction

The two-mass eigenstates of the neutral B meson system, carrying mass m_L and m_H, are expressed in terms of the flavor eigenstates, B^0 and $\overline{B}^0$, as $|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$.

If CP is violated in mixing, the probability of a B^0 to oscillate to a $\overline{B}^0$ is different from the probability of a $\overline{B}^0$ to oscillate to a B^0 and thus we expect to observe a sizeable value for the asymmetry:

$$\mathcal{A}_{CP} = \frac{N(B^0B^0) - N(\overline{B}^0\overline{B}^0)}{N(B^0B^0) + N(\overline{B}^0\overline{B}^0)} \simeq 2\delta_{CP}. \tag{1}$$

where $\delta_{CP} = 1 - |q/p|$.

Any deviation from unity of the ratio $|q/p|$ would imply that the mass eigenstates are not CP eigenstates ("mixing-induced CP violation"). The Standard Model prediction is $\mathcal{A}_{CP} = -(4.1 \pm 0.6) \times 10^{-4}$ [1]. A large deviation from $\delta_{CP} = 1$ would be therefore a clear evidence of New Physics beyond the Standard Model.

2 Analysis Method

We present a measurement based on the partial reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu_\ell}$ decays (hereafter $B_{\rm R}$). A state decaying as a B^0 ($\overline{B}^0$) meson produces a positive (negative) charge lepton. The observed asymmetry between the number of positive-charge and negative-charge leptons is therefore:

$$A_\ell \simeq \mathcal{A}_{r\ell} + \mathcal{A}_{CP}\chi_d, \tag{2}$$

where $\chi_d = 0.1862 \pm 0.0023$ [2] is the integrated mixing probability for B^0 mesons, and $\mathcal{A}_{r\ell}$ is the charge asymmetry in the reconstruction of $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu_\ell}$ decays.

We use kaons from decays of the other B^0 ($B_{\rm T}$) to tag its flavor (K_T). A state decaying as a B^0 ($\overline{B}^0$) meson results most often in a $K^+(K^-)$. If mixing takes place, the ℓ and the K have then the same electric charge. The observed asymmetry in the rate of mixed events is:

$$A_T = \frac{N(\ell^+K_T^+) - N(\ell^-K_T^-)}{N(\ell^+K_T^+) + N(\ell^-K_T^-)} \simeq \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}, \tag{3}$$

where $\mathcal{A}_K$ is the charge asymmetry in kaon reconstruction. A kaon with the same charge as the ℓ might also come from the Cabibbo-Favored (CF) decays of the D^0 meson produced with the lepton from the partially reconstructed side (K_R). The asymmetry observed for these events is:

$$A_R = \frac{N(\ell^+K_R^+) - N(\ell^-K_R^-)}{N(\ell^+K_R^+) + N(\ell^-K_R^-)} \simeq \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}\chi_d \tag{4}$$

Eqs. 2, 3, and 4 can be inverted to extract $\mathcal{A}_{CP}$ and the detector induced asymmetries.

3 Extraction of δ_{CP}

The data sample used in this analysis consists of an integrated luminosity of 425.7 fb^{-1}, corresponding to 468 million $B\overline{B}$ pairs, collected at the $\Upsilon(4S)$ resonance by the BABAR detector.

We select a sample of partially reconstructed B mesons by retaining events containing a charged lepton ($\ell = e$, μ) and a low momentum pion (soft pion, π_s^+) from the decay $D^{*+} \to D^0\pi_s^+$. The lepton momentum must be in the range $1.4 < p_{\ell^-} < 2.3\,\mathrm{GeV}/c$ and the soft pion candidate must satisfy $60 < p_{\pi_s^+} < 190\,\mathrm{MeV}/c$. Throughout the paper the momentum, energy and direction of all particles are computed in the e^+e^- rest frame.

Using conservation of momentum and energy, the invariant mass squared of the undetected neutrino is calculated as $\mathcal{M}_\nu{}^2 \equiv (E_{\rm beam} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$, where

E_{beam} is half the total center-of-mass energy and E_ℓ (E_{D^*}) and $\vec{p}_\ell$ ($\vec{p}_{D^*}$) are the energy and momentum of the lepton (the D^* meson). The D^{*+} four-momentum can be computed by approximating its direction as that of the soft pion, and parameterizing its momentum as a linear function of the soft-pion momentum. We select pairs of tracks with opposite electric charge for our signal ($\ell^{\mp}{\pi_s}^{\pm}$) and we use same-charge pairs ($\ell^{\pm}{\pi_s}^{\pm}$) for background studies.

We determine the number of signal events in our sample with a minimum χ^2 fit to the ${\mathcal{M}_\nu}^2$ distribution in the interval $-10 < {\mathcal{M}_\nu}^2 < 2.5$ GeV^2/c^4. A total of $(5945 \pm 7) \cdot 10^3$ peaking events are found. The result of the fit is displayed in Fig.1.

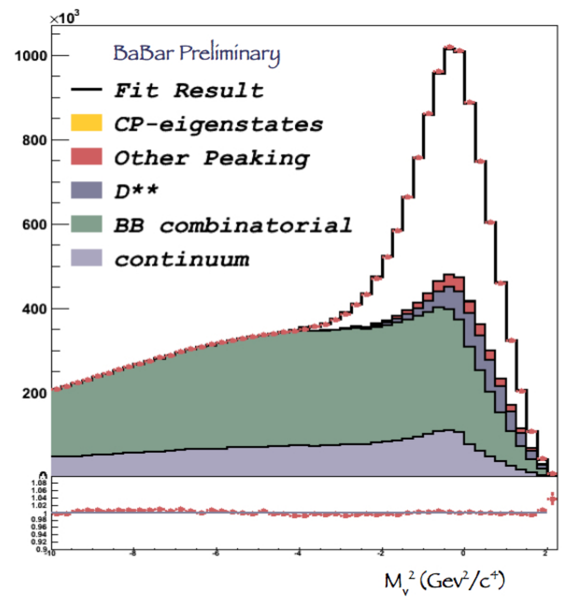

Figure 1: ${\mathcal{M}_\nu}^2$ distribution for the data, points with error bars, and the fitted contributions from the various sample components.

We define $\Delta Z = Z_{\rm R} - Z_{\rm T}$, where $Z_{\rm R}$ is the projection along the beam direction of the $B_{\rm R}$ decay point, and $Z_{\rm T}$ is the projection along the same direction of the intersection of the K track trajectory with the beam-spot. We measure the proper-time-difference between the two B mesons using the relation $\Delta t = \Delta Z/(\beta\gamma c)$, where the parameters β, γ express the Lorentz Boost from the laboratory to the $\Upsilon(4S)$ rest frame.

We distinguish K_T from K_R using proper-time difference and kinematic informations. Due to the short lifetime and small boost of the D^0 meson, small values of Δt are expected for the K_R. The ℓ and the D^{*+} are emitted at large angles in the rest frame of the decaying B^0: therefore the angle $\theta_{\ell K}$ between the ℓ and the K_R has values close to π, and $\cos(\theta_{\ell K})$ close to -1. The corresponding distribution for the

K_T is uniform.

The measurement proceeds in two steps. We first measure the sample composition of the eight tagged samples defined by lepton type, lepton charge and K charge, with the fit to $\mathcal{M}_\nu{}^2$ described above. The results of the first stage are used in the second stage, where we perform a binned maximum likelihood fit to a two-dimensional PDF obtained as a product of the Δt and $\cos(\theta_{\ell K})$ functions.

The Δt distributions for K_T $B\overline{B}$ events are parameterized as the convolutions of the theoretical distributions $\mathcal{F}_i(\Delta t'|\vec{\Theta})$ with the resolution function $\mathcal{R}(\Delta t, \Delta t')$: $\mathcal{G}_i(\Delta t) = \int_{-\infty}^{+\infty} \mathcal{F}_i(\Delta t'|\vec{\Theta})\mathcal{R}(\Delta t, \Delta t')d(\Delta t')$, where $\Delta t'$ is the actual difference between the times of decay of the two mesons and $\vec{\Theta}$ is the vector of the physical parameters.

The resolution function consists of the superposition of several Gaussian functions convolved with exponentials. We use a different set of parameters for peaking and for combinatoric events.

To describe the Δt distributions for K_R events, $\mathcal{G}_{K_R}(\Delta t)$, we select a sub-sample of data containing less than 5% K_T decays, and we use the background subtracted histograms in our likelihood.

The individual $\cos(\theta_{\ell K})$ shapes are obtained from the histograms of the simulated distributions for $B\overline{B}$ events, separately for K_T and K_R events.

Events belonging to each of the eight tagged samples are grouped in 100 Δt bins, 25 $\sigma(\Delta t)$ bins, 4 $\cos\theta_{\ell,K}$ bins, and 5 $\mathcal{M}_\nu{}^2$ bins. We further split data in five bins of K momentum, p_K, to account for the dependencies of several parameters, describing the Δt resolution function, the $\cos(\theta_{\ell K})$ distributions, and the fractions of K_T events, observed in the simulation.

The rate of events in each bin $(\vec{j})$ and for each tagged sample are then expressed as the sum of the predicted contributions from peaking events, $B\overline{B}$ combinatorial and continuum background.

Accounting for mistags and K_R events, the peaking B^0 contributions to the equal-charge samples are:

$$
\begin{aligned}
\mathcal{G}_{\ell^\pm K^\pm}(\vec{j}) = (1 \pm \mathcal{A}_{r\ell})(1 \pm \mathcal{A}_K)\{(1 - f^{\pm\pm}_{K_R})[(1-\omega^\pm)\mathcal{G}_{B^0B^0/\overline{B}^0\overline{B}^0}(\vec{j}) + \\
\omega^\mp \mathcal{G}_{B^0\overline{B}^0/\overline{B}^0B^0}(\vec{j})] + f^{\pm\pm}_{K_R}(1-\omega'^\pm)\mathcal{G}_{K_R}(\vec{j})(1 \pm \chi_d \mathcal{A}_{CP})\ \}
\end{aligned}
\tag{5}
$$

where the reconstruction asymmetries are computed separately for the e and μ samples. We allow for different mistag probabilities for K_T ($\omega^\pm$) and K_R ($\omega'^\pm$).

The $f^{\pm\pm}_{K_R}(p_k)$ parameters describe the fractions of K_R tags in each sample in terms of the kaon momentum. A total of 171 parameters are determined in the fit.

After unblinding we find: $\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$.

We consider several sources of systematic errors: uncertainties on the composition of the peaking and the combinatorial samples, on the description of the K_R and the CP eigenstate Δt distributions, and on the $\Delta\Gamma$ and Δm_d parameters. Parameterized simulations are used to check the estimate of the result and its statistical uncertainty.

The difference between the nominal result and the average of those obtained from pseudo-experiments is included in the total systematic uncertainty as well as the statistical error of a validation test performed using the simulation.

Fig. 2 shows the fit projections for Δt and $\cos\theta_{\ell K}$.

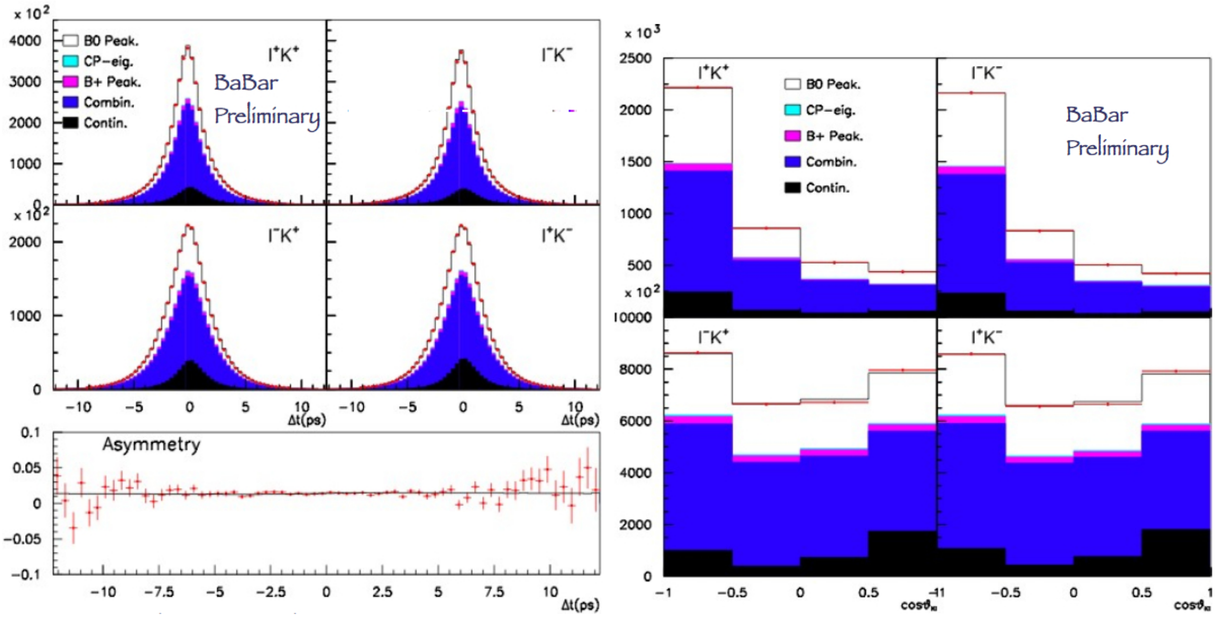

Figure 2: Δt (left) and $\cos\theta_{\ell K}$ (right) distributions for the data, point with error bars, and the fitted contributions from the various sample components. Bottom left plot: Raw asymmetry between ℓ^+K^+ and ℓ^-K^- events.

In summary, we present a new precise measurement of the parameters governing CP violation in $B^0\ \overline{B}^0$ oscillations. With a partial $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu_\ell}$ reconstruction and K tagging we find $\delta_{CP} = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$, and $\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$. These results are consistent with and more precise than the B-factories results from dilepton measurements. No deviation is observed from the SM expectation [1].

References

[1] A. Lenz, arXiv:1102.4274.

[2] J. Beringer *et al.*, (Particle Data Group), Phys. Rev. D86, 010001 (2012).